# Selenium in the New River and an Evaluation of Human Health Risk Reduction by the Brawley and Imperial Constructed Wetlands Demonstration Project (W-06-3)


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### Narrative Summary


Constructed wetlands are an attractive water treatment option, not only because of their low cost and minimal maintenance requirements, but because they may also provide critical wildlife habitat. The New River Wetlands Project is comprised of two constructed treatment wetland sites supplied with water from the New River and agricultural drainage water from the Imperial Valley in California. It was hoped that these wetlands would reduce levels of pollutants, including selenium, in the New River before it discharges to the Salton Sea.

Selenium levels in water (at wetland inflow and outflow), sediments, plants, invertebrates, and fish were analyzed for both wetland sites from 2006-2007. An average of 56% of the total mass of selenium in the inflow was removed at the Imperial site, and 70% was removed at the Brawley site. Most of the retained selenium (17 kg at the Imperial site and 4 kg at the Brawley site) was in the sediments. Less than 1% of the selenium accumulated in plant tissues. Mass balance calculations estimated that up to 33-50% of the selenium was lost through volatilization.

After six years of operation of these wetlands, concentrations of selenium in fish and invertebrates were at or above threshold ranges for reproductive effects in birds and fish. Constructed wetlands are an efficient method for removing selenium from agricultural drainwater, although they need to be monitored over the long-term for potential risks posed by bioaccumulation of selenium.

# SELENIUM IN THE NEW RIVER AND AN EVALUATION OF HUMAN HEALTH RISK REDUCTION BY THE BRAWLEY AND IMPERIAL CONSTRUCTED WETLANDS DEMONSTRATION PROJECT

# Project Number: W-06-3


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### INTRODUCTION

The New River has been contaminated for many years by untreated sewage flows and agricultural drain waters, which have raised concern for public and ecological health via a variety of exposure scenarios to waters of the New River and the Salton Sea. Constructed wetlands have been used successfully for water treatment, and they are an attractive treatment option because of their low cost and minimal maintenance (Gersberg, et al. 1983; Hansen, et al. 1998). The Imperial and Brawley wetlands are two constructed treatment wetlands sites adjacent to the New River in the Imperial Valley of southeastern California. The wetlands treat agricultural drainwaters and New River water, respectively, thereby reducing levels of pollutants, including selenium, before discharge to the Salton Sea, California. Although supplies of irrigation water to the Imperial Valley have selenium levels around 2 µg/L (Setmire and Schroeder 1998), selenium is concentrated through excessive irrigation and evaporation in the Imperial Valley, resulting in selenium levels of 6 to 28 µg/L, with average concentrations of selenium at 8 µg/L (Setmire and Schroeder 1998). The presence of selenium in industrial or agricultural discharges in some parts of the world is a concern because it biomagnifies and is an ecological threat at elevated levels (Ohlendorf 1986).

Lin and Terry (2003) showed that constructed wetlands can remove up to 69 percent of the dissolved selenium in agricultural drainwater. However, there is little published data on the removal of selenium from agricultural drainwaters flowing into the Imperial and Brawley constructed wetlands in Imperial Valley, California. Furthermore, the efficiency of removal, fate of selenium, and resultant ecological risk in these wetlands is not clearly understood.

In the future, as much as 4,000 acres of such constructed wetlands are planned for water quality improvement at the New River (Citizens Congressional Task Force on the New River). Data on the effects of the wetland will be extremely valuable in indicating how effective constructed wetlands are at removing contaminants such as viruses and selenium in the New River, and what factors are critical to full time design and operation of a constructed wetland. The objective of the present study was to assess the efficiency of the Imperial and Brawley constructed wetlands at removing selenium and to estimate the fate of selenium and ecological risk posed by such selenium loading to these wetlands.

## RESEARCH OBJECTIVES

During the first year of this project, we were unsuccessful at developing a quantitative and dependable real-time PCR assay for viruses in the New River. Apparently the presence of high concentrations of humic substances or other inhibitory materials (e.g. heavy metals) in the New River made the viral recovery method recalcitrant to such investigation by PCR methods. With this in mind, soon after the beginning of this project, work on these constructed wetlands shifted in focus to investigating selenium removal in the Brawley and Imperial constructed wetlands, since the biomagnification of selenium is an emerging issue in the Salton Sea area.

### *Selenium Removal in the Brawley and Imperial Constructed Wetlands*

Constructed wetlands are an attractive water treatment option, not only because of their low cost and minimal maintenance (Gersberg, et al., 1983; Hansen, et al., 1998), but because they may also provide critical wildlife habitat. Two pilot-scale constructed wetlands were built in the Imperial Valley (California) to test the suitability of constructed wetlands for treating agricultural drain waters and water from the New River. It was hoped that these wetlands would reduce levels of pollutants, including selenium, in the New River before it discharges to the Salton Sea.

Although supplies of irrigation water to the Imperial Valley have selenium levels of approximately 2 µg/L (Setmire and Schroeder, 1998), selenium is concentrated through excessive irrigation and evaporation in the Imperial Valley, resulting in selenium levels of 6 to 28 µg/L, with an average of 8 µg/L (Setmire and Schroeder, 1998) in agricultural drain waters. The presence of selenium in industrial or agricultural discharges in some parts of the world is a concern because it biomagnifies and is an ecological threat at elevated levels (Ohlendorf, 1986). Since the United States Environmental Protection Agency (USEPA, 2000) water quality criterion is 5 µg/L, the selenium levels in the constructed wetlands may adversely impact wildlife.

At present, it is unknown whether constructed wetlands in the Imperial Valley can effectively remove selenium from agricultural drainwaters. Furthermore, the efficiency of removal, fate of selenium, and resultant risks to wildlife in these wetlands from selenium are all unknown in the Imperial Valley, where selenium is a primary concern. The objectives of the present study were the following:

1. Assess the efficiency of the Imperial and Brawley constructed wetlands at removing selenium
2. Model the fate of selenium in the constructed wetlands,
3. Evaluate the risk selenium may pose to wildlife in these systems.

## Research Methodology/Approaches

*Site Description*

The two wetlands are located along the New River, in southern California. The Brawley wetlands are located just south of the city of Brawley (32°57’33” N, 115°34’12” W), while the Imperial wetlands are located to the south of the Brawley wetlands, just to the west of the city if Imperial (32°52’30” N, 115°39’03” W). Average yearly inflows for the two wetlands are 0.031 and 0.18 $cm^3/s$, respectively, and average yearly outflows are 0.014 and 0.11 $cm^3/s$, respectively (Imperial Irrigation District, unpublished data). Temperatures in the area typically average 13 degrees C in the winter and 32 degrees C in the summer. Rainfall in this area is usually very low, at 9 cm per year, while evapotranspiration rates are high, at 3 m/year.

The Imperial wetlands site is supplied with agricultural drainwater from the “Rice Drain agricultural drain. It consists of 17.5 hectares, with 1.2 hectares vegetated with bulrush (*Schoenoplectus californicus*), tamarisk (*Tamarix spp*.), and wild grasses. The wetland receives approximately 11,000 cubic meters of water per day with a residence time of 18 days. The Brawley wetlands site, which is supplied with New River water, is comprised of 3.6 hectares, with 0.5 hectares vegetated with bulrush, tamarisk, and wild grasses. The Brawley wetland receives approximately 2,700 cubic meters of water per day with a residence time of 9 days. Both of the wetlands sites are unlined and, therefore, allow a portion of the inflowing water to seep into the ground. Ducks, cormorants, and various wading birds frequent both wetlands. Other biota in the wetlands include muskrats, fish, crayfish, shrimp, and algae. The sampling locations at the Imperial and Brawley wetlands are shown in Figures 1 and 2, respectively.

*Sample Collection*

Water was sampled periodically during the study period of June 2006 through June 2007, and sediment, plant, invertebrate, and fish samples were collected in May 2006. All water samples were collected, preserved, and analyzed for selenium using U.S Environmental Protection Agency (EPA) method 200.8 (USEPA, 1994). Sediments, plants, invertebrates, and fish were transported in plastic bags and frozen until analysis.

*Sample Digestion and Analysis*

Sediment samples were dried at 60°C to a constant weight and digested per EPA method 3051A (USEPA, 1998). The plant shoot and root samples were rinsed with deionized water to ensure they were free of sediment, dried at 60°C to a constant weight and digested per EPA method 3052 (USEPA, 1996). Eleven fish were dissected to obtain muscle tissue. The fish muscle samples were dried at 40°C to a constant weight and digested per EPA method 3052, using only 2 ml of concentrated nitric acid in a PTFE digestion vessel and microwave digestion system obtained from CEM Corporation. Whole fish and invertebrate samples were analyzed per EPA method 200.8 (USEPA, 1994). All samples were analyzed using an inductively-coupled plasma – mass spectrometer (ICP-MS).

*Quality Control / Quality Assurance*

Certified reference materials were processed identically to samples and the recoveries were calculated based on the known reference concentrations. The following Standard Reference Materials (SRM) from the National Institute of Standards and Technology were analyzed: SRM #1640 Trace Elements in Natural Water, SRM #2709 San Joaquin Soil, and SRM #1515 Apple Leaves. Additionally, DORM-2 Dogfish Muscle Certified Reference Material for Trace Metals, certified by the National Research Council of Canada, was analyzed. Laboratory method blanks were processed for each matrix using preparation methods identical to the samples, and at least one duplicate sample for each matrix was prepared and analyzed.

*Statistical Analysis*

A Wilcoxon signed-rank test was conducted to compare the median differences in selenium concentrations between the inflows and the outflows of each wetland. A Mann-Whitney U test was conducted to compare the difference between the median selenium levels in the roots and shoots at each wetland site.

*Selenium Mass Balance*

Selenium may be retained in wetlands in the sediments or biomass, and lost from the system via outflow, seepage into ground, or volatilization. A water balance using historic flows (Imperial Irrigation District, unpublished data), and accounting for evapotranspiration loss (estimated at 3 m/year), yielded seepage loss rate estimates of 20.2 m/year at Imperial and 17.2 m/year at Brawley. Then, assuming that a variable fraction of the selenium seeping into the ground was immobilized into the sediments via reduction to insoluble forms (Cooke and Bruland, 1987), estimations for the range of selenium lost through volatilization can be made. Selenium lost by volatilization was calculated as the difference between the mass of selenium in the inflow and the mass in the outflow plus that stored in the sediments and/or lost via seepage. Once this was done, a mass balance for selenium was developed under two scenarios, each reflecting an upper and a lower range of the estimate of selenium volatilization.

## RESEARCH FINDINGS

*Quality Assurance/Quality Control*

The percent recoveries (%R) with the coefficient of variation (%CV) of 5 replicates of the standard reference materials were as follows: Water (100%R, 8%CV), soil (87%R, 19%CV), leaves (325%R, 9%CV), and fish (147%R, 10%CV). The concentrations of selenium in the method blanks were below the detection limit (0.1 ppb). The mean coefficient of variation between 8 duplicate readings for water was 0.1%. The coefficients of variation between duplicate samples of the other matrices were as follows: sediments (2%CV), shoots (4%CV), roots (23%CV), and fish (8%CV).

*Selenium Removal Efficiency of the Wetlands*

Since the majority (96% for Imperial and 95% for Brawley) of selenium in the inflows to both wetlands was dissolved selenium (Tetra Tech, 2006), measurements of total dissolved selenium were used to evaluate selenium removal efficiency by these wetlands. Total dissolved selenium concentrations in the inflows (IW0 and BW0) and outflows (IW10 and BW6) of the Imperial and Brawley wetlands are presented in Figures 3 and 4. At the Imperial site, selenium concentrations ranged from 2.7-5.4 µg/L in the inflow and from 2.0-4.8 µg/L in the outflow, with a mean selenium removal efficiency of 22 ± 14 percent. At the Brawley site, selenium concentrations ranged from 2.2-3.9 µg/L in the inflow and from 1.1-2.0 g/L in the outflow, with a mean selenium removal efficiency of 42 ± 13 percent. Levels of selenium in the outflows were significantly lower than inflow levels at both wetlands (Wilcoxon signed-rank test, $n = 11$, $p=0.01$).

*Selenium Mass Balance*

Selenium mass removal was calculated as the product of the inflow concentration and the average inflow rate minus the product of the outflow concentration and the average outflow rate (inflow and outflow rates obtained from Imperial Irrigation District, unpublished data). Mass selenium removal efficiency was 56 percent (± 8%) for the Imperial wetlands and 70 percent (± 7%) for the Brawley wetlands from June 2006 to February 2007 (Figure 5). Mass selenium removal efficiency was higher than that calculated for selenium concentrations (Figures 3 and 4) due to the water lost to seepage and selenium lost to immobilization processes.

Selenium concentrations in sediments, plants, invertebrates, and fish are presented in Table 1. Selenium levels in sediments ranged from 0.2-0.8 and 0.4-0.5 mg Se/kg, for the Imperial and Brawley sites, respectively. Concentrations of selenium found in the shoots at the Imperial and Brawley sites ranged from 0.1-1.2 and 0.2-.5 mg Se/kg, respectively. Concentrations were higher (Mann-Whitney U test, $n = 16$, $p=0.01$) in the roots than in the shoots, from 1.6-16.0 and 0.6-3.1 mg Se/kg for the Imperial and Brawley sites, respectively. Selenium levels in fish muscle tissue ranged from 1.0 to 2.7 mg Se/kg at the Imperial site, and from 0.4 to 2.8 mg Se/kg at the Brawley site.

Selenium levels in whole fish ranged from 3.3 to 20.0 mg Se/kg at the Imperial site, and from 1.9 to 7.3 mg Se/ kg at the Brawley site. Selenium levels in invertebrates ranged from 2.8 to 5.2 mg Se/kg at the Imperial site, and from 1.5 to 8.2 mg Se/kg at the Brawley site.

Selenium may be retained in wetlands in the sediments or biomass, and lost from the system via outflow, seepage into ground, or volatilization. An estimate of selenium retained in biomass using levels directly measured in shoot and root tissue, showed that biomass could only account for a very small fraction (< 1%) of the selenium in the inflow. Sedimentation rates measured directly in these wetlands (Tetra Tech, 2006) showed an accumulation rate of about 5.33 cm/year. Using this with the measurements of selenium in the sediments as a function of depth, the mass of selenium stored in the sediments was estimated at approximately 17 kg in the Imperial wetlands and 4 kg in the Brawley wetlands.

A water balance using historic flows (Imperial Irrigation District, unpublished data), and accounting for evapotranspiration loss (estimated at 3 m/year), yielded seepage loss rate estimates of 20.2 m/year at Imperial and 17.2 m/year at Brawley. Then, assuming that a variable fraction of the selenium seeping into the ground was immobilized into the sediments via reduction to insoluble forms (Cooke and Bruland, 1987), estimations for the range of selenium lost through volatilization can be made. A mass balance for selenium within each wetland is presented in Table 2. Two separate scenarios are presented, reflecting an upper and a lower range of the estimate of selenium volatilization.

Scenario 1 (Table 2) assumes that all of the selenium in the water that seeped into the ground was reduced to insoluble forms and immobilized within the wetland sediments. Scenario 2 (Table 2) assumes that all of the selenium in the seepage waters remains soluble and is lost from the wetlands system into the ground. Under Scenario 1, 33% and 50% of the selenium in the inflow at the Imperial and Brawley sites respectively, was unaccounted for and assumed to be lost due to volatilization. Under Scenario 2, 17% and 39% of the selenium in the inflow was unaccounted for in the Imperial and Brawley wetlands, and assumed to be lost due to volatilization (Table 2). It was estimated that 123 kg of selenium entered and 66 kg flowed out of the Imperial wetlands, and 18 kg entered and 5 kg flowed out of the Brawley wetlands.

*Selenium Removal in Wetlands*

Selenium removal efficiencies at the Imperial and Brawley wetlands sites during the study period were 22 and 42 percent, respectively (Figures 3 and 4). Mass selenium removal efficiencies were 56 percent at the Imperial site and 70 percent at the Brawley site (Figure 5). Mass removal is a better measure of efficiency than the percent reduction in concentration, since any loss of water through seepage (in these unlined wetlands), and via evapotranspiration will tend to concentrate the selenium in the wetland system. Lin and Terry (2003) found 69 percent selenium mass removal efficiency in agricultural drainwater by constructed wetlands in Corcoran, California, and

Hansen, et al. (1998) found that 89 percent of the mass of selenium in oil refinery wastewater was removed by constructed wetlands adjacent to San Francisco Bay, California. In a constructed wetlands microcosm, 79 percent of the mass of selenium in electric utility wastewater was removed by a constructed wetland microcosm (Ye, et al., 2003).

Retention time is an important factor in selenium removal efficiency by a wetland (Chow, et al., 2004). The wetlands studied by Lin and Terry (2003) had a retention time of 7-21 days and a mass removal efficiency of 69 percent. The retention times of the Imperial and Brawley wetlands were within the same range (18 and 9 days, respectively), and although the mass removal efficiency was similar for the Brawley site (70%), it was lower for the Imperial site (56%). Surprisingly, although the retention time of the Imperial wetlands was twice as long as the Brawley wetlands, the removal efficiency was lower. The retention time of the wetlands studied by Hansen, et al. (1998) was in the same general range (7-10 days) as the Imperial and Brawley wetlands, but the removal efficiency was higher (89%). It is difficult to explain differences in selenium removal efficiencies based on retention time alone, since there are other factors involved, including vegetation, microbial activity, and seasonal differences (Lin and Terry, 2003).

*Selenium Volatilization*

The selenium mass balance calculated for each wetland (Table 2) results in a range of values for the percent selenium volatilized in the wetlands. Using the mass balance calculation (Table 2), it was estimated that between 17% and 50% of the selenium at the two constructed wetland sites was lost through volatilization. Cooke and Bruland (1987) estimated, through similar mass balance calculations, that 30 percent selenium volatilized from the Kesterson Reservoir ponds. Hansen, et al. (1998) measured selenium volatilization by direct assay and calculated rates up to 30 percent from oil refinery wastewater. Moreover, Lin and Terry (2003) demonstrated, through direct measurements of selenium volatilization, that rates were up to 48% during the summer and less than 5% during the winter. The preponderance of estimates of selenium loss due to volatilization (including our own) shows losses in the range of 17-50%.

*Ecological Risk*

Selenium levels in all but one water sample measured on February 4, which was 5.4 µg/L (Figure 3), were less than 5 µg/L, the EPA criterion for protection of aquatic life (USEPA, 2000). However, levels of selenium in the water at the wetlands are above the toxic threshold (2 µg/L) for food-chain bioaccumulation and reproductive failure in fish and aquatic birds, as recommended by Lemly (2002). Studies on agricultural irrigation drainwater in the western United States have shown that selenium may accumulate to toxic levels (i.e., 10-20 mg Se/kg) in the food chain even when water concentrations do not exceed 3 µg/L (Lemly, 2002).

On the other hand, sediments analyzed in the present study do not exceed the toxic threshold (Lemly, 2002). The concentrations of selenium in sediments were below 1 mg Se/kg, which is within that considered as background (i.e., 0.2-2.0 mg Se/kg) by the United States Department of the Interior's National Irrigation Water Quality Program (NIWQP, 1998). Concentrations of selenium measured in the plant shoots (0.2-1.2 mg Se/kg) were well within NIWQP background concentration for freshwater plants (i.e., 0.1-2.0 mg Se/kg) (NIWQP, 1998). The selenium concentrations in the plant roots were significantly higher though (0.6-16.0 mg Se/kg) (Table 1) (Mann-Whitney U test, $n = 16$, $p = 0.01$). This is consistent with the studies by Hansen, et al. (1998) and Ye et al. (2003), which also found higher selenium concentrations in roots compared to the shoots. Currently there are no standard criteria for selenium in sediments or aquatic plants.

Concentrations of selenium in most of the invertebrates and whole fish at both the Imperial and Brawley wetlands sites (Table 1) were within the range of NIWQP criteria (i.e., 3-8 mg Se/kg dry weight) where reproductive impairment may be expected in birds (from the consumption of aquatic biota). One composite (tadpoles at the Brawley site) was above this range (8.2 mg Se/kg dry weight), which suggests reproductive effects may be of concern. The fact that mosquito fish at the Imperial wetlands had concentrations of selenium (6.1 mg Se/kg dry weight) at the high end of the NIWQP threshold range for reproductive effects in sensitive fish species (i.e., 4-6 mg Se/kg dry weight) suggests reproductive effects may be of concern. Mean selenium concentrations in whole mosquito fish from the Brawley site, in all other fish (whole) at the Imperial site, and in some of the fish at the Brawley site (Table 1) were within the range of this threshold. The background selenium concentration for whole fish is < 1-4 mg Se/ kg (NIWQP, 1998).

## CONCLUSIONS

Constructed wetlands are an effective treatment method for removing selenium from agricultural drainwater, with 56 and 70 percent mass selenium removed at the Imperial and Brawley wetlands, respectively. Volatilization loss estimated by mass balance calculation ranged from 17 to 50 percent at the two constructed wetland sites. After six years of operation, levels of selenium in some of the fish and invertebrates at the wetlands were at or above threshold ranges for reproductive effects in birds and fish, indicating that selenium could be a concern for the future operations of these constructed wetlands sites.

## PROBLEMS/ISSUES ENCOUNTERED

During the first year of this project, we were unsuccessful at developing a quantitative and dependable real-time PCR assay for viruses in the New River. Apparently the presence of high concentrations of humic substances or other inhibitory materials (e.g. heavy metals) in the New River made the viral recovery method recalcitrant to such investigation by PCR methods. With this in mind, soon after the beginning of this project, work on these constructed wetlands shifted its focus to investigating selenium removal in the Brawley and Imperial constructed wetlands since the biomagnification of selenium is an emerging issue in the Salton Sea area.

## RESEARCH BENEFITS

Publications that have been published or submitted as a result of this project include:

*Policy and Decision-making Arena*

The Good Neighbor Environmental Board, an independent U.S. Presidential advisory Board, has as its mission is to advise the President and Congress of the United States on “good neighbor” environmental and infrastructure practices along the U.S. border with Mexico. The results of our work on both the Brawley and Imperial wetlands were included in the most recent Report of the GNEB (12$^{th}$ Report: Innovative and Practical Approaches to Solving Border Environmental Problems. The following statement is excerpted from this report: “Researchers from San Diego State University, supported by the Southwest Consortium for Environmental Research and Policy (SCERP), have been evaluating the fate and removal of selenium in these constructed wetlands. Their findings determined that constructed wetlands are an efficient method for removing selenium from agricultural drainwater; however, after 6 years of operation of these wetlands, concentrations of selenium in fish and invertebrates were at or above threshold ranges for reproductive effects in birds and fish.

In a similar regard, the results of the present SCERP Project on the Brawley and Imperial Constructed Wetlands were helpful in providing feedback to Mr. Doug Liden of the U.S. EPA Border Office on any concerns/problems that might arise from selenium for a Border 2012 proposed project in Mexicali, “the Creation of Constructed Wetlands to Treat Wastewaters in Las Arenitas” a project of the Sonoran Institute and the Comisión Estatal de Servicios Públicos de Mexical (CESPM).

*Scientific field, including publications*

A paper was prepared and is now published (in press) in the peer-reviewed journal Ecological Engineering. The full citation is: **Johnson, P.I**., Gersberg, R.M, Rigby, M. and S. Roy. 2009. The fate of selenium in the Imperial and Brawley constructed wetlands in Imperial Valley, California. Ecological Engineering, In Press

*Education and Training of Students*

This project contributed significantly to the education and training of a number of graduate students including those who co-authored the publications referenced above (names in boldface). Additionally the Masters student, Laurel Cutter, finished her MPH thesis entitled “Evaluating the Efficiency of Hepatitis A Virus and Enterovirus Removal in a Constructed Wetlands on the New River in Imperial County, California.  At present, another Masters Student, Marcelo Braga, is working on his thesis supported by this grant. The focus of his work is to directly measure the rate of selenium volatilization in the Brawley and Imperial Constructed Wetlands. Additionally, an international Ph.D student, Anne Becker , is currently on a J-1 Visa from the University of Kassel and the University of Magdeburg, Germany to do her research on the ecological functioning of the constructed wetlands in Imperial County.

## ACKNOWLEDGMENTS

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## APPENDIX

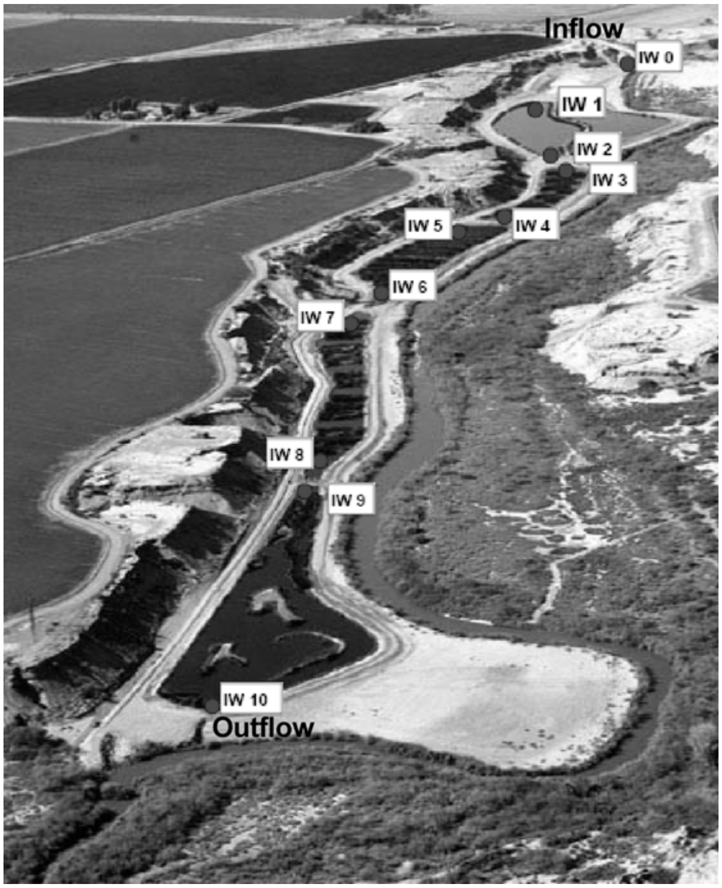


Figure 1. Aerial Photograph of Imperial Wetlands Site. Photograph is labeled with sample collection locations. Source: New River Wetlands Project, Retrieved March 12, 2007 from newriverwetlands.com/frameset2.html


Figure 2. Aerial Photograph of Brawley Wetlands Site. Photograph is labeled with sample collection locations. Source: New River Wetlands Project, Aerial wetlands photos. Retrieved March 12, 2007 from newriverwetlands.com/frameset2.html

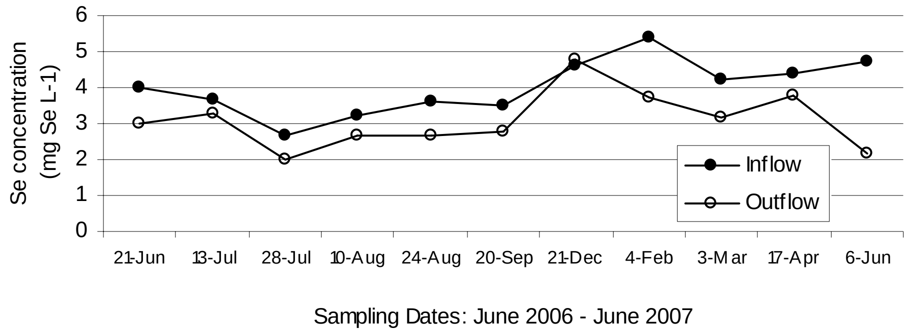


Figure 3. Concentrations of Total Dissolved Selenium in the Inflow and Outflow at the Imperial Wetlands

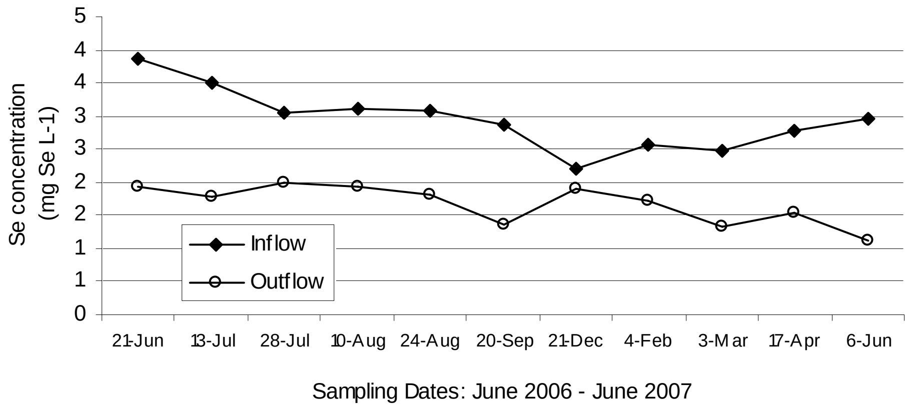


Figure 4. Concentrations of Total Dissolved Selenium in the Inflow and Outflow at the Brawley Wetlands

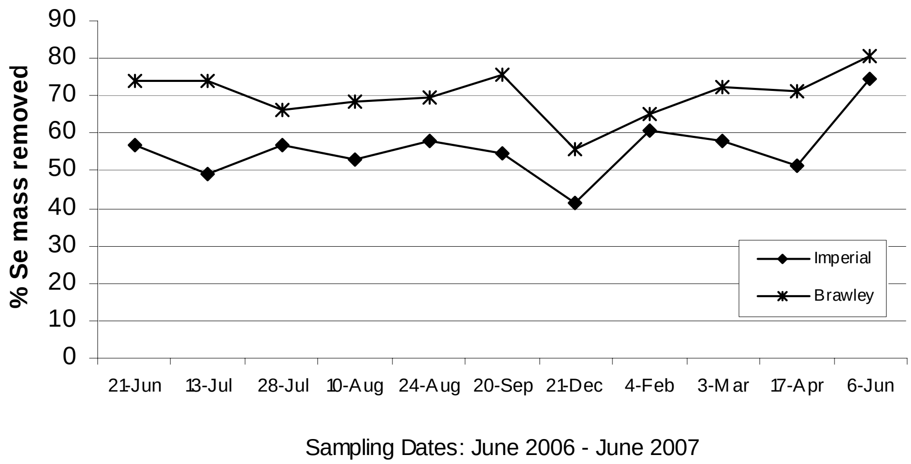


Figure 5. Percent Selenium Mass Removed from Inflow After Passage Through the Constructed Wetlands

Table 1. Selenium Concentrations (geometric means) in Sediments, Plants, Invertebrates, and Fish (dry weight)

| *Se concentration (mg Se $kg^{-1}$) | Imperial | | Brawley | |
|---|---|---|---|---|
| | n | GM +/- GSD | n | GM +/- GSD |
| Sediments | 6 | 0.4 +/- 1.9 | 7 | 0.5 +/- 1.1 |
| Shoots | 11 | 0.5 +/- 2.2 | 6 | 0.4 +/- 1.4 |
| Roots | 9 | 5.7 +/- 2.1 | 7 | 1.7 +/- 2.0 |
| Muscle Tissue | 6 | 1.5 +-/ 1.6 | 5 | 0.7 +/- 2.2 |
| Mosquito fish | 9 | 6.1 +/- 1.9 | 6 | 4.2 +/- 1.3 |
| Carp | 26 | 4.5 +/- 1.3 | 7 | 4.3 +/- 1.1 |
| Shad | 36 | 4.6 +/- 1.2 | 15 | 2.7 +/- 1.3 |
| Tilapia | - | - | 6 | 4.9 +/- 1.2 |
| Glass shrimp | 1 | 5.2 | 5 | 3.5 +/- 0.8 |
| Crayfish | - | - | 2 | 2.6 +/- 1.6 |
| Tadpoles | - | - | 1 | 8.2 |
| Dragonfly larvae | 1 | 4.1 | 1 | 2.5 |
| Corixids | 6 | 3.9 +/- 1.3 | 9 | 3.3 +/- 1.6 |

*Sediment samples were grabs from collection sites IW1, IW2, IW6, IW8, IW10 and BW1-BW6. Shoots and roots (*Schoenoplectus californicus*) sampled were from IW1-IW10 and BW1-BW10. Fish sampled were mosquito fish (IW1-10 and BW1-6), carp (IW1-7, 10 and BW1, 4), shad (IW1-5, 8-10 and BW1-4) and tilapia (BW1, 2, 4). Invertebrates sampled were corixids (IW4-7), crayfish (BW2), glass shrimp (IW7 and BW1-5) and dragonfly larvae (IW8 and BW5). Numerous individuals were composited for each analysis.

Table 2. Mass Balance for Selenium in the Imperial and Brawley Constructed Wetlands

Scenario 1: Se reduced to insoluble forms

| | Imperial | | Brawley | |
|---|---|---|---|---|
| | Se (kg) | % of Inflow | Se (kg) | % of Inflow |
| Inflow | 123 | | 18 | |
| Outflow | 66 | 54% | 5 | 28% |
| Sediments | 17 | 14% | 4 | 22% |
| Volatilized | 40 | 33% | 9 | 50% |

Scenario 2: Se seeped into ground with water

| | Imperial | | Brawley | |
|---|---|---|---|---|
| | Se (kg) | % of Inflow | Se (kg) | % of Inflow |
| Inflow | 123 | | 18 | |
| Outflow | 66 | 54% | 5 | 28% |
| Seepage | 36 | 29% | 6 | 33% |
| Volatilized | 21 | 17% | 7 | 39% |